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Maximum power point tracking control techniques: State-of-the-art in photovoltaic applications

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A B S T R A C T

A photovoltaic (PV) array has non-linear *I–V* (current–voltage) characteristics and its output power varies with solar insolation level and ambient temperature. There exists only one point, called maximum power point (MPP), on the *P–V* (power–voltage) curve, where power is maximum and this point varies with the changing atmospheric conditions. Moreover, energy conversion efficiency of PV module is very low and mismatch between source and load characteristics causes significant power losses. Consequently, maximization of power output with greater efficiency is extremely important. Maximum power point tracking (MPPT) is a technique employed to extract maximum power available from the PV module. It traces the PV operating voltage corresponding to the MPP and locks the operating point at MPP and extract maximum power from the array. Till date, many algorithms for MPPT have been reported, each with its own features. In this paper, a comprehensive presentation of working principle of these techniques is made and they are compared against each other in terms of some critical parameters like: number of variables used, complexity, accuracy, speed, hardware implementation, cost, tracking efficiency and so on. This study is aimed at providing a compendium on MPPT techniques for an appropriate selection, based on application requirements and system constraints.

Contents

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1. Introduction

As energy demand continues to increase, efforts are being made towards new energy sources and also towards increasing energy output from existing ones. Solar energy is considered to be one of the most reliable and promising source of renewable energy. It offers various significant advantages in terms of being pollution-free, quiet in operation, long life, low maintenance, zero input energy cost (and running cost) and inexhaustible sun power as input energy source. Photovoltaic technology is undergoing development in two specific ways: cell material and power conditioner (DC/DC and/or DC/AC converters) technology, with the objective to increase overall conversion efficiency. Despite advancement in solar cell materials, from polycrystalline, mono crystalline to amorphous and thin film, the energy conversion efficiency still remains poor and system cost is very high. Thus, the performance of power conditioner plays a significant role in enhancing overall power conversion efficiency and reduction in cost.

PV arrays have non-linear I–V characteristics and output power depends on atmospheric conditions. There exists only one point, maximum power point (MPP) on the P–V curve, that is the knee, where power is maximum [1]. MPPT is a technique employed to extract maximum power available from the PV source, as location of MPP keeps on varying with changing atmospheric conditions [1–3]. The MPP tracker traces, PV operating voltage corresponding to MPP and locks the operating point at MPP and extract maximum power from the PV array [2–6].

A large number of conventional MPPT techniques, have been reported in literatures [7–58]. Selection of a particular MPPT technique from a number of existing techniques is a confusing task, since each technique has certain advantages and disadvantages. The review papers in literatures although present comparative study of different MPPT algorithms [59–68], yet are confusing sometimes. The commonly known MPPT techniques in literatures are: Voltage based and current based [6–15], perturb and observation (P&O) [16–23], incremental conductance (INC) [29–32], sliding mode control [41–44], fuzzy logic control based (FLC) [53–58] etc.

The P&O and INC methods are widely reported conventional methods with certain advantages and disadvantages. P&O technique has a problem of oscillations around MPP, due to which there is considerable loss of power [16]. Also the response of P&O algorithm is slow under fast changing environmental condition [23] and variable step size Incremental Resistance method (INR) may overcome the disadvantages of P&O and INC method [33].

The Voltage based MPP tracking algorithm is proposed in [6–15], though seemingly simple yet with low accuracy and efficiency [14]. Among other methods, the Gradient descent method overcomes the drawbacks of commonly used method as it uses variable step size technique [48]. Ripple correlation control (RCC) method has certain advantages over P&O methods and are discussed in [34–38]. Slide mode control technique, though complex in hardware implementation but is more accurate than conventional methods [41–44]. Temperature method of MPPT is reported in [45–47], requires less number of sensors than conventional methods. This method is simple in implementation and is economical also. Apart from this there is another method called Bisection Search Theorem based MPPT reported in [40] which is mostly used when PV array exhibits two or more local MPP's under varying climatic conditions, where use of other techniques is a difficult task. A Dual tracking system which includes a mechanical tracker and an electrical MPPT, both controlled by two separate DSPs is reported in [58]. It uses fuzzy logic controller (FLC) based and P&O based MPPT tracking as electrical tracker [58].

Different techniques as discussed in different literatures have certain advantages and disadvantages with respect to different performance indices. An attempt is made in this paper to discuss

in detail the working principle of different MPPT techniques and to compare their performances. The performances of different techniques are compared on the basis of desirable features like: complexity, speed, hardware implementation, sensors required, cost, and range of effectiveness, dynamic response, steady state error, stability and efficiency of the system.

The paper is organized in following sections: Section 2, deals with the modelling of PV panel. To understand the need of MPPT, PV cell model and its characteristics are discussed in detail in Section 2.1 and effect of temperature and insolation on PV cell characteristics is discussed in Section 2.2. Section 3 addresses the need of MPPT and classification of different MPPT techniques. Section 4 presents comprehensive review of different MPPT techniques in detail along with their limitations, deficiencies and advantages. Section 5 deals with the analysis, comparison and weighing of different MPPT techniques on the basis of different performance indices. Finally, conclusions are given in Section 6.

2. Modelling of PV panel

2.1. Equivalent model and I–V characteristics of PV cells

The PV cell is a kind of non-linear DC current source; it supplies variable power which depends, on variation of the temperature and insolation. The equivalent circuit of PV cells can be represented by either The venin's circuit or by Norton's circuit. The equivalent circuit of PV cell is as shown in Fig. 1

$$I_{PV}=I_L-I_0\left[\exp^{\left((V_{PV}+R_SI_{PV})/(V_T)\right)}-1\right]-\frac{V_{PV}+R_SI_{PV}}{R_P} \qquad (1)$$

The *I–V* characteristics is given mathematically by Eq. (1), where I_{PV} and V_{PV} is the PV output current and output voltage, respectively, I_0 is reverse saturation current, R_S is the series cell resistance, R_P shunt resistance, $I_L=N_PI_{PH}$ are the light generated current of the solar array, I_{PH} is the cell generated current and N_P are the number of parallel modules, $I_O=N_PI_{OS}$, where I_{OS} is the cell saturation current. $V_T=((N_S\, n\, K_B\, T)/(q))$ is the thermal voltage N_S, is the no of cells connected in series, n is the ideality factor, K_B is the Boltzmann's constant, T is the cell temperature [2–5]. The output characteristic (current and voltage) of a PV array is influenced by solar irradiation, temperature, wind speed, humidity, pressure etc. [3]. The irradiation and temperature are two primary factors which influences the power output of the panel most, they are discussed in detail in Section 2.2

2.2. Effect of temperature and insolation on solar cell characteristics

The temperature of the PV solar cell increases due to three reasons: (i) due to its own heat during photovoltaic action, (ii) the energy radiated at the infrared wavelength which has a heating effect on the cell and (iii) due to increase in solar insolation [3].

$$V_{oc}=V_{oc}^{*}+a_2(T-T^{*})-(I_{SC}-I_{SC}{}^{*})\,R_S \qquad (2)$$

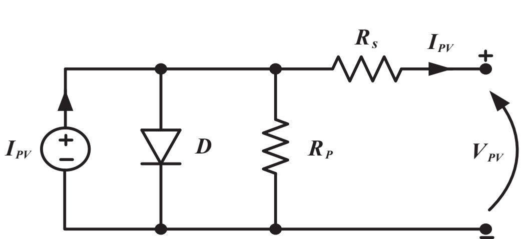

Fig. 1. Equivalent circuit diagram of solar cell.

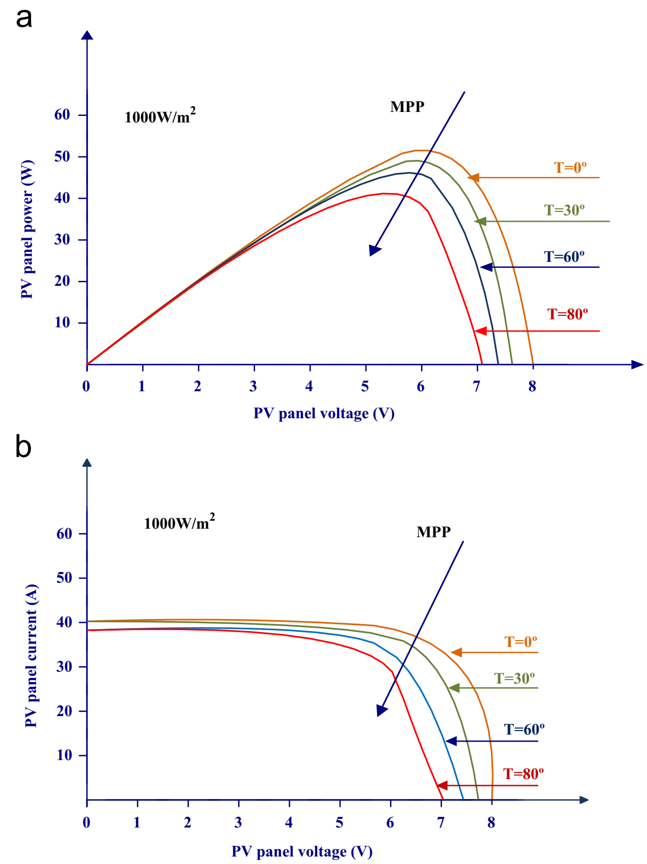

Fig. 2. (a) *P–V* characteristic at constant insolation and different temperatures. (b) *I–V* characteristic at constant insolation and different temperatures.

$$I_{sc}=I_{SC}{}^{*}\left(\frac{G}{G^{*}}\right)+a_1(T-T^{*}) \qquad (3)$$

Eqs. (2) and (3), gives open circuit voltage and short circuit current, respectively, of PV array at solar intensity (G) and cell temperature (T) [5]. Where solar intensity (insolation) is the power radiated from sun and is measured in W/m^2. In Eqs. (2) and (3), I_{SC}^{*} and V_{oc}^{*} are the short circuit current and open circuit voltage at the reference solar intensity G^{*} and reference solar temperature T^{*}, a_1 and a_2 are the PV cell temperature coefficients for current and voltage, respectively [5]. The *P–V* curve and *I–V* curve of PV panel corresponding to different temperatures and at constant insolation as per Eqs. (2) and (3) are shown in Fig. 2(a) and (b). It shows that output power of the PV panel decreases with the increase in temperature [5], implying that a cooler panel produces more power than the hotter one. The open circuit voltage decreases linearly with increase in cell temperature, while short circuit current slightly increases with cell temperature.

The photo current I_{PH} and hence the PV panel short circuit current depends on the insolation and temperature as given in Fig. 3(a) and (b) which implies as radiations increases, the current and hence power increases [3,4]. The open circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation.

3. MPPT techniques: Necessity and classification

3.1. Need of MPPT

The efficiency of PV system can be improved if the PV array is operated intentionally at MPP, irrespective of varying

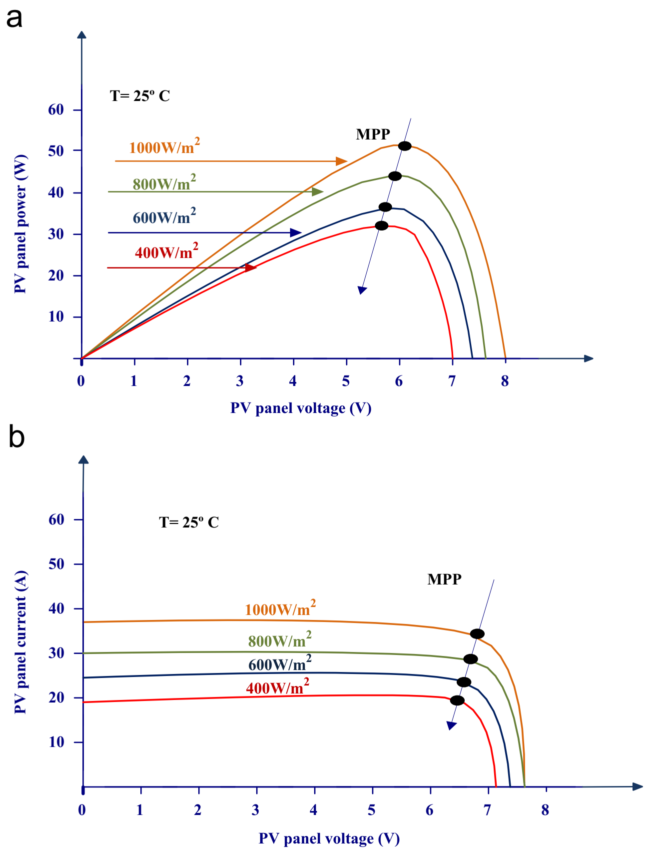

Fig. 3. (a) *P–V* characteristics at constant temperature and different insolations. (b) *I–V* characteristics at constant temperature and different insolations.

atmospheric conditions. This can be done by properly matching PV source with the load for any weather condition, to achieve maximum power generation. The technique by which the maximum power point on the *P–V* curve is been tracked electrically, MPP is located and maximum power is extracted for different environment conditions is called maximum power point tracking (MPPT). There are two ways by which maximum power can be extracted from PV array they are: Mechanical tracking and Electrical tracking (MPPT). Mechanical tracking is a physical tracking process in which orientation of PV panel is changed at a pre-calculated and pre-defined angle throughout day along with the position of sun. The orientation of PV panel is also changed with months and seasons throughout year. This change in orientation can be manual or automatic. Electrical tracking (MPPT) is a process in which *I–V* curve of the panel is tracked for MPP. Usually power electronics devices are used in renewable energy power generation as electrical trackers. They can track the MPP in order to achieve maximum efficiency and can also convert DC power to AC power as required by stand-alone system or grid so as to comply with power quality requirements of the power system.

A power converter device mostly, DC/DC(buck/boost/buck–boost type) converter along with inverter (two-stage conversion) or inverter alone (single-stage conversion) as shown in Fig. 4 is used in between the PV module and the load (stand-alone or grid) to achieve MPPT. These converters use some algorithm, to ensure that the PV module always operates at its MPP these algorithms are called MPPT techniques. A digital controller (microcontroller or DSP) is used to control the converter, to implement these algorithms and perform the function of MPPT. To extract maximum power from PV system a number of MPPT methods (electrical) have been proposed in literature [6–58].

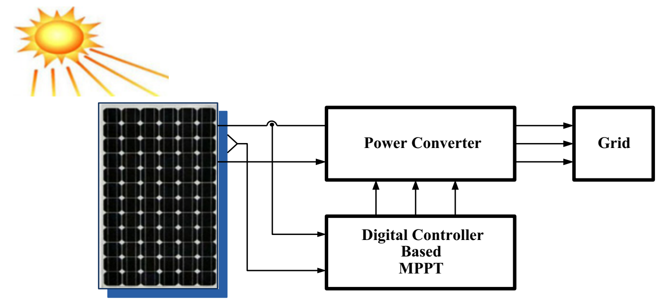

Fig. 4. Block diagram of MPPT controller for photovoltaic system.

3.2. Classification of MPPT techniques

There are different ways of classifying MPPT techniques, some based on the number of variables used to track MPP like one variable or two variable methods, and some based on the type of techniques used to track MPP. The different MPPT control techniques in this paper are classified into broadly three groups: *Offline* (*indirect*), *Online* (*direct*) and *other techniques*, mainly on the basis of parameters required to track MPP. Fig. 5 depicts classification of different MPPT techniques.

Offline control techniques usually use technical data of PV panels to estimate the MPP. These data includes prior information like, *I–V* and *P–V* curves of the panels for different climatic conditions, different mathematical models etc of PV panels. Online (direct) methods on the other hand use real time, PV voltages and/or current measurements for tracking MPP. These methods do not require the measurement of temperature and solar irradiance and also the PV array model. The offline methods are cost effective but performance wise less effective than online and other methods. Other methods include either modification or combination of these methods or methods based on indirect calculations.

4. Review of various MPPT techniques

4.1. Voltage (open circuit voltage) and current (short circuit current) based MPPT.

Voltage-and current-based MPPT are also called mathematical computational methods [6]. In this method, the non linear *I–V* characteristics of solar panels are modelled, which are true for different atmospheric conditions. In both the methods, system requires a DC/DC converter which operates in buck or boost mode. The driver circuit for this converter and also the shunt and the series switch is controlled by a microcontroller or DSP [6–15]. The process of sampling of short circuit current or open circuit voltage, computing of maximum current or maximum voltage and adjusting the duty cycle is repeated to track MPP.

4.1.1. Current (short-circuit) based MPPT

$$I_{MPP} \cong K_{mi} I_{SC} \quad (4)$$

Eq. (4) is the basis of current based technique. I_{MPP} and I_{SC} are PV panel current during MPP and short circuit condition resp. K_{mi} is proportionality constant called *current factor* its value varies from 0.7 to 0.9 depending upon cell material and characteristic of panel used [6]. Where [6] did not take into account the temperature dependency in the above equation, since K_{mi} is not always constant, but varies with the surface conditions of the PV panel. Eq. (4) is plotted in Fig. 6. Hardware consists of a shunt switch (power electronic) for measurement of short-circuit current by

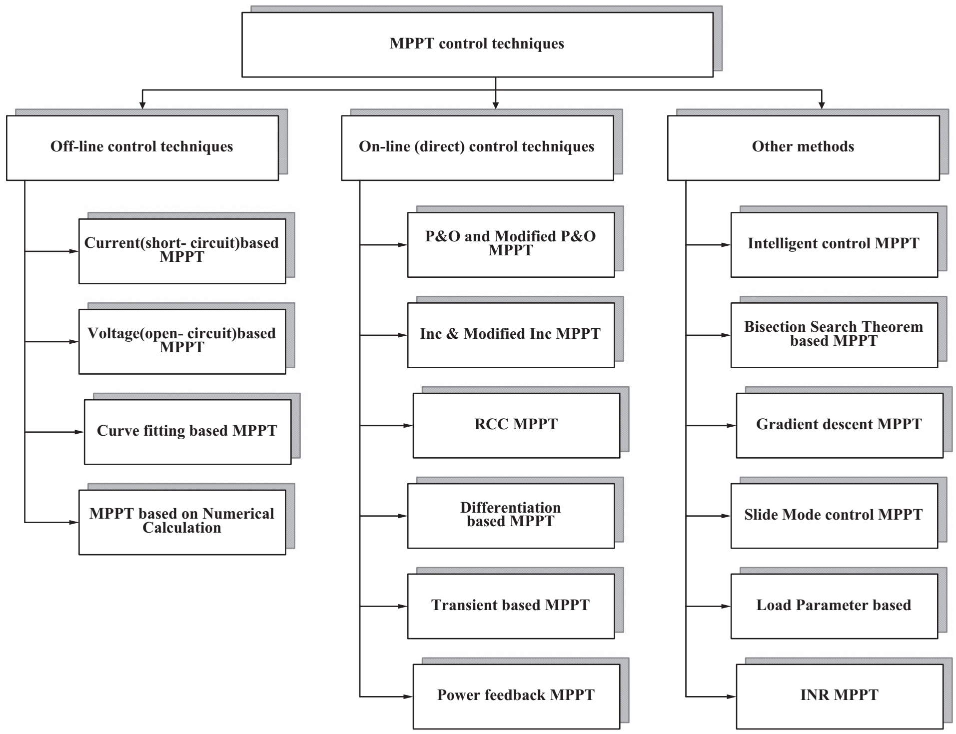

Fig. 5. Classification of MPPT techniques.

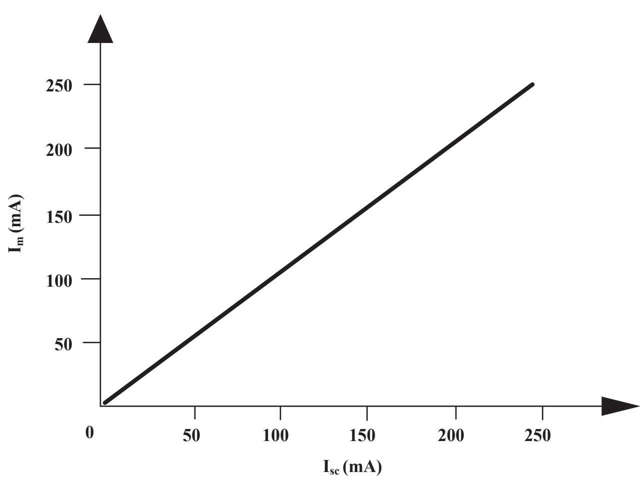

Fig. 6. Plot pertaining to Eq. (4).

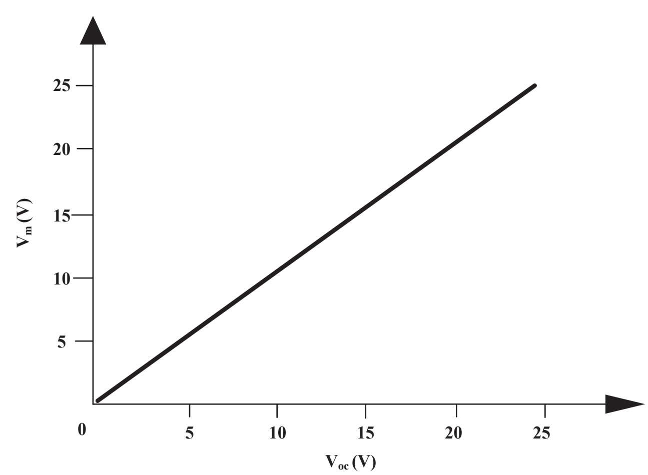

Fig. 7. Plot pertaining to Eq. (5).

short circuiting the panel [7]. The I_{MPP} can be computed by using proportional controller after a hold circuit whose coefficient is K_{mi}. Short-circuit current of the panel (I_{SC}) is sampled periodically and from Eq. (4) once K_{mi} is known, I_{MPP} can be calculated for different sampled values of I_{SC}. The duty cycle of DC/DC converter is increased or decreased so that output current becomes equal to I_{MPP} [8].

4.1.2. Voltage (open-circuit) based MPPT

The maximum power point voltage V_{MPP} and open circuit voltage V_{OC} have a linear dependence for different solar radiation and operating temperatures. This is the key to develop voltage MPPT technique. Eq. (5) gives relation between V_{MPP} and V_{OC} [9].

$$V_{MPP} \cong K_{mv} V_{OC} \tag{5}$$

where K_{mv} is called *voltage factor* and its value ranges from 0.7 to 0.95 depending upon the characteristics of the PV panel [10] (Fig. 7). In voltage based method, a series switch placed in between panel and converter, does the measurement of open circuit voltage. The MPPT momentarily sets the PV array current to zero by open circuit and measure V_{OC} then V_{MPP} is calculated according to Eq. (5). The MPPT controller then, controls the duty cycle to obtain load voltage equals to V_{MPP}. This process is repeated periodically to get maximum power [14,15].

Tracking speed of both techniques are high, as no derivatives are required to be calculated, sensors required are less and are practical method for MPP estimation [13]. But major problem with both the techniques is loss of power during sampling of short circuit current and open circuit voltage. The current based method requires hardware which is more complicated and expensive as shunt switch is required and has more losses as compared to voltage based method, hardware of same rating [14]. Accuracy of current based technique is more compared to voltage

based technique whereas, voltage based technique is more efficient and has fewer losses [13]. The advantage of this method is that it is simple and economic and uses only one feedback loop, but disadvantage is that it is not effective in varying temperature and insolation conditions also this method cannot be applied in the battery energy storage system. This method is used in case where insolation does not changes much for example satellite system [13].

4.2. Look-up table method

This is one of the offline methods of tracking MPP. In this method prior knowledge of PV panel material, technical data, panel characteristics at different environmental conditions are required and are stored. Then the PV panel output current I_{PV} and output voltage V_{PV} are sensed power is calculated and compared with those of stored values to track MPP and operating point is shifted to new maximum power point. Thus large amount of data is required to be stored before actually tracking MPP and system requires a large memory capacity to store prior data. Also, system becomes complex for varying atmospheric conditions [64]. This method is not very accurate method of MPP tracking, number of sensors required is more and also speed of this method is slow.

4.3. Curve- fitting-based MPPT

The curve-fitting techniques is an offline technique where PV panel characteristics, technical data and other manufacturing details are required, also mathematical model and equations describing the output characteristics are decided in advance. This method is based on different models of PV panels and uses mathematical equations for these models. Based on the mathematical model and equations used, the voltage corresponding to MPP is calculated and the operating point on the characteristics of the panel is moved to track the MPP [64]. One of such model, where PV panel characteristic is given by Eq. (6) where α, β, γ, and δ are coefficients determined by sampling k values of PV panel output voltage V_{PV}, PV current I_{PV} and output power P_{PV} [64]. Once these coefficients are calculated the voltage at MPP can be calculated by using Eq. (7) and MPP can tracked.

$$P_{PV} = \propto V_{PV}{}^{3} + \beta\, V_{PV}{}^{2} + \gamma\, V_{PV} + \delta \tag{6}$$

At Maximum power point, $dP_{PV}/dV_{PV}=0$

$$V_{MPP} = \frac{-\beta \pm \sqrt{\beta^2 - 3\alpha\gamma}}{3\alpha} \tag{7}$$

The advantage of this method is its simplicity, as no differentiations are to be calculated but disadvantage is that it requires prior knowledge of the PV model, mathematical equations and parameter dependence on cell material and specifications. Also, it requires large memory as the number of calculations is large. Speed is less as large computation time is required to calculate α, β, γ, and δ for different environmental conditions.

4.4. The perturb and observe method (P&O) and modified P&O MPPT

P&O is an iterative method of MPPT tracking [16–23]. It senses the panel operating voltage periodically calculates and compares the PV output power with that of the previous power, then the operating voltage is changed by changing the duty ratio and change in the direction of power is observed to track MPP. The sign of change in power is used, if the power increases by increasing voltage then the operating voltage is further perturbed in the same direction as shown in Fig. 8, this process continues till $dP/dV=0$ [16]. As soon as the MPP is reached, the voltage oscillates around the MPP, instead of being stably positioned on it, as voltage perturbation continues at MPP also. This is one of the biggest disadvantages of this method. Also, as the voltage is perturbed periodically considerable power loss takes place [16]. So this method does not gives good results under rapidly changing atmospheric conditions as shown in P–V curve in Fig. 9, also speed of this method is slow as it tracks the MPP in several steps [17]. However, this method has an advantage of not requiring solar panel characteristics.

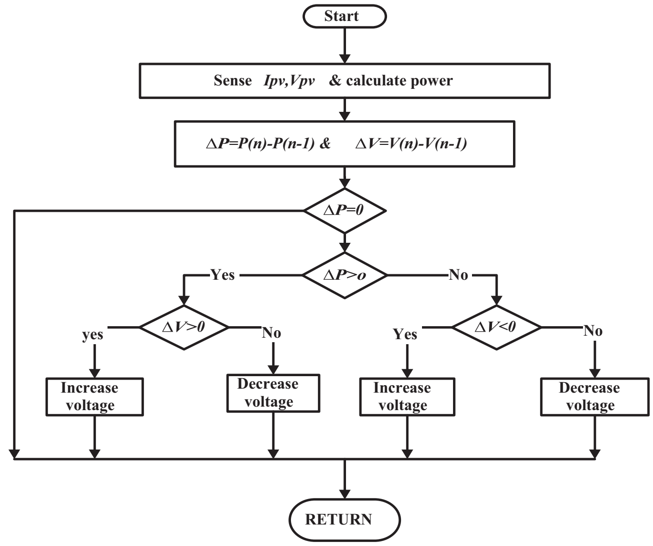

Fig. 8. Flow chart of P&O algorithm.

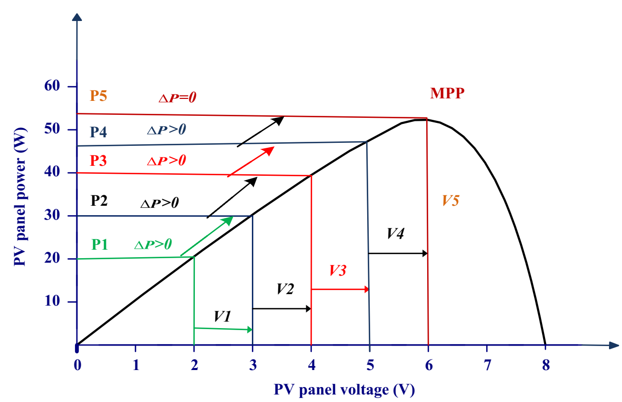

Fig. 9. P–V Curve for P&O algorithm.

As shown in Fig. 8, PV panel output voltage V_{PV} and output current I_{PV} are sensed. Then power is calculated $P(n)$ and compared with the power measured in the previous sample $P(n-1)$, in order to get ΔP. Then according to the sign of ΔP and ΔV, the duty cycle of the converter is changed to track MPP as summarized below [16–23].

- If the value of ΔP is zero, the system is working at MPP and no change in duty cycle is required as shown in Fig. 9.
- If the value of $\Delta P > 0$ and $\Delta V > 0$, the operating point is located on the left of MPP and duty cycle is to be increased to increase the voltage so as to reach MPP.
- If the value of $\Delta P > 0$ and $\Delta V < 0$, the operating point is toward right of MPP and duty cycle must be decreased to reach MPP.
- If the value of $\Delta P < 0$ and $\Delta V < 0$, the operating point is towards left of MPP and duty cycle is to be increased to reach MPP.

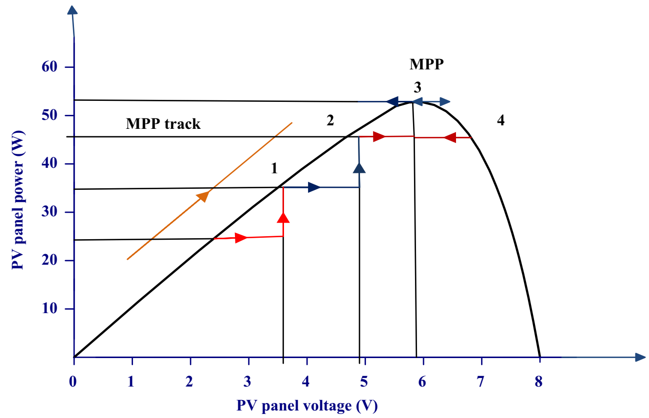

Fig. 10. Implementation of P&O method, showing oscillations around MPP.

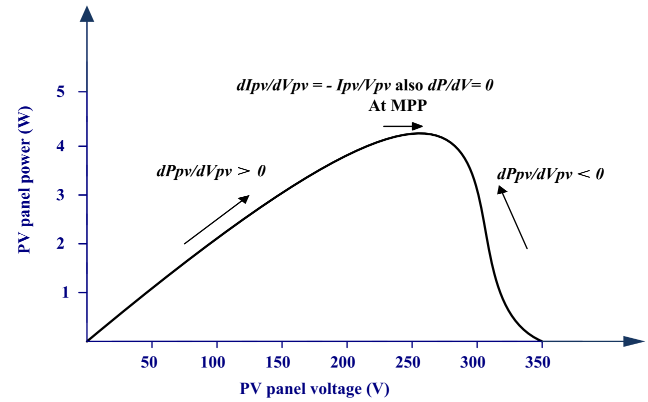

Fig. 11. *P–V* curve for INC MPPT.

- And if the value of $\Delta P<0$ and $\Delta V>0$, the operating point is towards right of MPP and duty cycle this time is to be decreased to reach MPP.

The conventional P&O technique tracks the MPP by perturbing the PV panel voltage or current and moves the control variable towards the MPP with fixed step size as in Fig. 10. The fixed step size tracking have certain disadvantages like slow speed and large steady state oscillations [25]. If large steps are chosen, it will result in faster dynamics but steady state oscillations also increases and efficiency decreases [26]. On the other hand if small steps are chosen dynamics will slow down [24]. So to overcome this problem of fixed steps, adaptive (modified) P&O algorithms [25–28] are used which uses adaptive step size to increase tracking speed and reduce steady state oscillations.

4.5. Incremental conductance method (INC) and modified INC MPPT

INC technique is widely used MPPT technique [29–32]. The disadvantage of P&O method, of oscillation of operating point around MPP during changing environmental conditions can be eliminated in INC method by comparing the instantaneous panel conductance (I_{PV}/V_{PV}) with the incremental panel conductance (dI_{PV}/dV_{PV}). The voltage of MPP is tracked to satisfy $dP_{PV}/dV_{PV}=0$, which is MPP. INC based algorithm is advantageous over other conventional methods because it is easy to implement, high tracking speed and better efficiency [32].

Output power from solar panel is: P_{PV} = PV array output power

$$P_{PV}=V_{PV}\,I_{PV} \tag{8}$$

Differentiating Eq. (8) with respect to V_{PV} gives

$$dP_{PV}/dV_{PV}=I_{PV}+V_{PV}\,(dI_{PV}/dV_{PV}) \tag{9}$$

This equation is the basis of INC algorithm as shown in *P–V* curve Fig. 11, at MPP

$$dP_{PV}/dV_{PV}=0 \tag{10}$$

$$\mathrm{d}I_{PV}/\mathrm{d}V_{PV}=-I_{PV}/V_{PV} \tag{11}$$

If the operating point is on the right of the power curve then we have

$$dP_{PV}/dV_{PV}<0 \tag{12}$$

If the operating point is on the left of the power curve then we have

$$dP_{PV}/dV_{PV}>0 \tag{13}$$

In this algorithm the present and previous values of the solar panel voltage and current are sensed and are used to calculate the values of dI_{PV} and dV_{PV}. The algorithm is as shown in Fig. 12 for current based incremental conductance MPPT, similar algorithm exists for voltage based control where voltage is sensed compared and changed. Hardware required is as shown in Fig. 13(a)

If $dV_{PV}=0$ and $dI_{PV}=0$, then there is no change in atmospheric conditions and the MPPT is still operating at MPP where $dP_{PV}/dV_{PV}=0$, reference voltage is equal to maximum voltage for this atmospheric condition and is not changed that is there is no perturbation until a change in current is sensed.

- If $dV_{PV}=0$ and $dI_{PV}>0$, if the amount of insolation increases, the PV power increases raising the MPP voltage. This requires the MPPT to increase the operating voltage to track the MPP as shown in Fig. 13(b).
- On the other hand if $dI_{PV}<0$, decrease in insolation lowers the PV power and also lowering the MPP voltage and this requires the MPPT to decrease the PV array operating voltage.
- If $dI_{PV}/dV_{PV}>-I_{PV}/V_{PV}$, then $dP_{PV}/dV_{PV}>0$, and the PV array operating point is to the left of the MPP on the *P–V* curve. Thus, the PV panel voltage is to be increased to reach the MPP.
- Similarly, if $dI_{PV}/dV_{PV}<-I_{PV}/V_{PV}$, then $dP_{PV}/dV_{PV}<0$ and the PV panel operating point lie to the right of the MPP on the *P–V* curve and the voltage must be reduced to reach the MPP.

The duty cycle of the DC/DC converter is changed accordingly which changes the PV operating voltage to track the MPP [30,31].

The problem of fixed small or large steps can be resolved, if MPPT with variable step size is used, where the algorithm changes the step size automatically according to the PV array characteristics as suggested in the variable step size (Modified) INC MPPT algorithm [32]. If the operating point is far from MPP, the step size is increased, which enables fast tracking ability, if the operating point is near to the MPP, the step size becomes very small so that the oscillations are reduced contributing to higher efficiency. This technique gives very good results during rapidly changing atmospheric conditions with minimal oscillations and a good compromise between dynamic and steady state response [32].

4.6. Variable step-size incremental- resistance (INR) MPPT

The disadvantages of fixed step size MPPT techniques are oscillations around MPP and slow speed; these can be overcome in variable step size INR method [33]. This problem can be overcome if variable steps are used, which are usually large when

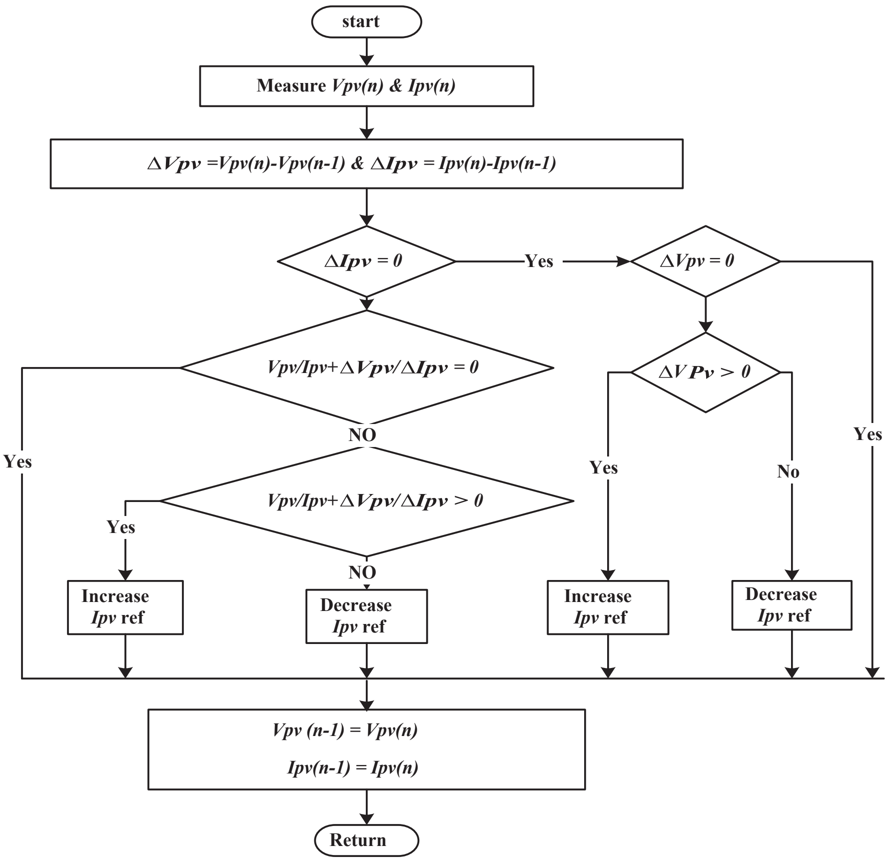

Fig. 12. Flow chart of INC method.

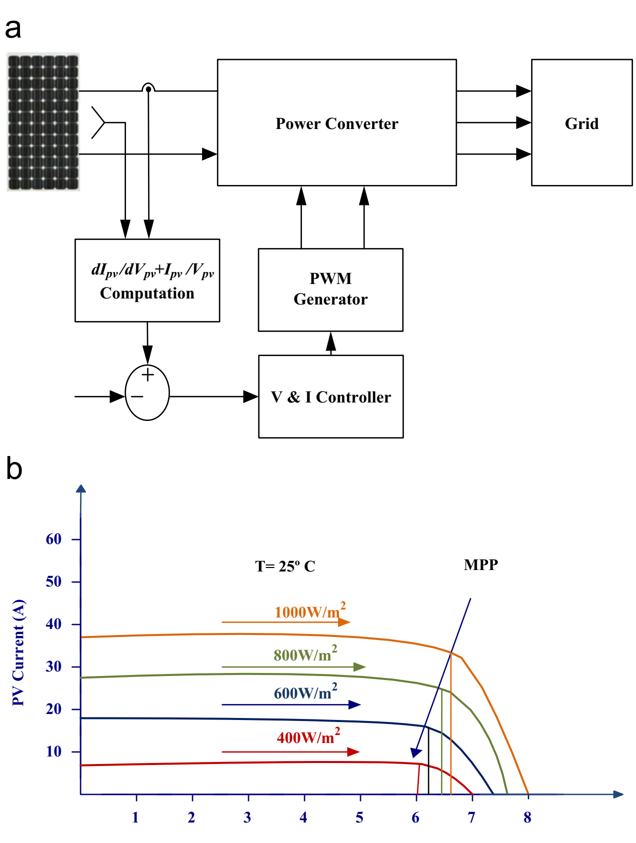

Fig. 13. (a) Hardware required for INC MPPT. (b) *I–V* curve for INC MPPT.

the system is away from MPP giving faster speed and step size becomes small as system approaches MPP which reduces oscillations around MPP. Usually variable step size methods are based on Eq. (14):

$$D(n) = D(n-1) \pm K(dP_{PV}/dV_{PV}) \tag{14}$$

where $D\,(n)$ is the duty ratio at sample n and $D\,(n-1)$ is the duty ratio at sample $n-1$ and K is the step size factor to control step size [33].

$$\frac{d\,P_{PV}}{d\,I_{PV}} = \frac{d(I_{PV}V_{PV})}{d\,I_{PV}}V_{PV} + I_{PV}\frac{d\,V_{PV}}{d\,I_{PV}} \tag{15}$$

$$\frac{d\,V_{PV}}{d\,I_{PV}} = -\frac{V_{PV}}{I_{PV}} \quad \text{at MPP} \tag{16}$$

$$\frac{d\,P_{PV}}{d\,I_{PV}} > -\frac{V_{PV}}{I_{PV}}, \quad \text{left of MPP} \tag{17}$$

$$\frac{d\,P_{PV}}{d\,I_{PV}} < -\frac{V_{PV}}{I_{PV}}, \quad \text{right of MPP} \tag{18}$$

The slope of PV array power curve is zero at MPP. The slope is positive to the left and negative to the right of MPP [33]. Thus as in INC method of tracking, in this method the instantaneous resistance is compared with incremental resistance and accordingly MPP is tracked. This method is based on current mode control.

4.7. Ripple correlation control (RCC) MPPT

This algorithm uses ripples in conversion system to achieve MPP, thus external changes are not used but are drawn from the system itself [34–38]. This technique is termed as “Physics based

technique" [34]. This method is applicable in a single stage configuration. The switching of the power converters causes voltage, current and hence power ripples, these ripples are used to track MPPT. The time derivative of the time varying power and time derivative of the time varying current or voltage of the panel is controlled to track MPPT so that the change in power at MPP is zero. The ripples (high frequency) in power and voltage are captured using filters which are then used to find out dP_{PV}/dV_{PV} [38]. The variation in dP_{PV}/dV_{PV}, is then used to track MPP. Thus the basic principle of this MPPT algorithm is to use the current and voltage oscillations caused by the pulsations of the instantaneous power. These oscillations give information about the power gradient and allow us to track MPP since the instantaneous power pulsates at a frequency which is double the frequency of the grid. This method uses the double-frequency oscillations of the instantaneous power as perturbation signals [38].

Whenever there is a change in atmospheric condition, the time derivative of voltage or current will also increase. And if power increases, the time derivative of power also increases, and then the operating point is below MPP. On the other hand if voltage or current is increasing and power is decreasing, the time derivative of power is negative and the operating point is above MPP. The voltage of the inverter is controlled in order to obtain the sinusoidal current output of the inverter in phase with the fundamental component of source voltage. The amplitude of the source current is generated by the DC link voltage regulator on the basis of the error between the DC link voltage and the reference DC voltage of the panel and this reference DC voltage is varied by the MPPT algorithm according to the environmental conditions in order to track MPP. Thus RCC gives a relation between the time derivative of power with the time derivative of current or voltage. These time derivatives are not zero due to the natural ripples during high frequency conversion so this method is named as "Ripple correlation" control [35].

This method has various advantages like in this method MPP tracking speed can be very high same as power converter switching speed, it has best initialization time as compared to P&O, INC and temperature method [67], and it is very accurate also though it is complex to implement because of electromagnetic interference issues if used on converter frequency.

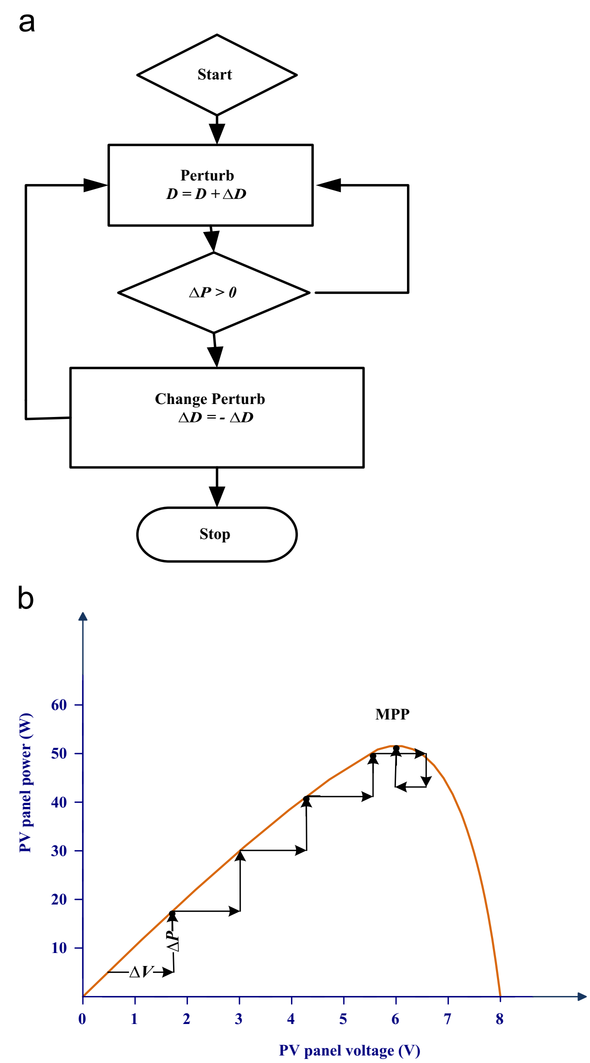

Fig. 14. (a) Flow-chart depicting Hill climbing method. (b) *P–V* curve for Hill climbing method.

4.8. Power feedback method (hill climbing method)

This method compares current power output of PV panel P_{PV} (n) with the power output in the previous sample P_{PV} $(n-1)$, which is obtained by sampling voltage and current periodically as depicted in Fig. 4(a) and (b). According to the change in power, duty cycle (D) of the DC/DC converter is changed, process repeats till MPP is reached, so maximum power point is achieved if the change in power with respect to duty cycle is forced to zero by the MPPT controller [39].

Since the plot of duty cycle and PV output power is hill shaped and change in PV output power with respect to duty cycle at MPP is zero, this method is also called hill climbing method. This method is simple in implementation but does not gives good results during rapidly changing atmospheric condition [39] (Fig. 14).

4.9. Bisection search theorem (BST) MPPT

This technique is simple in hardware requirement, as it requires no derivative calculations, economic in implementation as number of sensors required are less and method is fast in MPP tracking. The BST is a mathematical method for finding roots of equations [40]. This theorem states that, any function $y=f(x)$, which is dependent on x and contains a root x^*, at q between intervals $[p, r]$ such that the function $(dy/dx)=0$. In the case of PV, $P_{PV}=f(V_{PV})$ is the function and root V_{MPP} lies between interval $[0, V_{OC}]$ where $(d P_{PV}/d V_{PV})=0$, which is MPP as shown in Fig. 15(a). This point q where the function is zero can be obtained using bisection search theorem which moves the extreme point p and r closer by having the interval in each step such that $q=(p+r/2)$, that is $(0+V_{OC}/2)$ in the case of MPP and then checks the sign of the function as shown in Fig. 15(a)–(c).

- If $f(r)$ that is $(dP_{PV}/dV_{PV})|_{at\ V_{PV}=V_{OC}}$ and $f(q)$ that is $(dP_{PV}/dV_{PV})|_{at\ V_{PV}=V_1}$ have the opposite signs, root lies in $[r, q]$ that is $[V_1, V_{OC}]$.
- If $f(q)$ and $f(p)$ that is $(dP_{PV}/dV_{PV})|_{at\ V_{PV}=0}$ have opposite sign, root lies in $[q, p]$ that is $[0, V_1]$.
- If $f(q)=0$, then root is q that is MPP.

In first two cases the roots can be obtained by further halving the intervals. This BST is applied to track the maximum power point in the following way.

From the *P–V* curve, it can be observed that panel output power is a function of panel output voltage and change in power with respect to voltage, $\Delta P=(dP_{PV}/dV_{PV}) = 0$ at MPP also. It can be observed that when the panel is open circuited $V_{PV}=V_{OC}$,

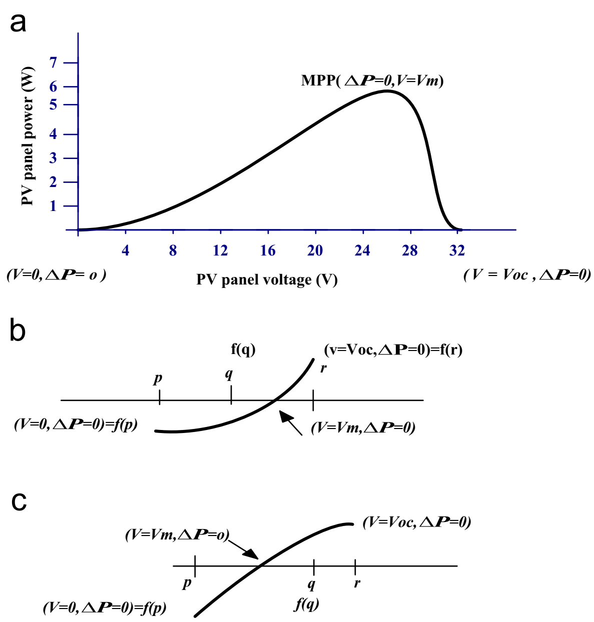

Fig. 15. Bisection search theorem for MPPT. (a) P–V curve of PV panel. (b) If $f(g)$ and $f(r)$ have opposite sign. (c) If $f(p)$ and $f(q)$ have opposite sign.

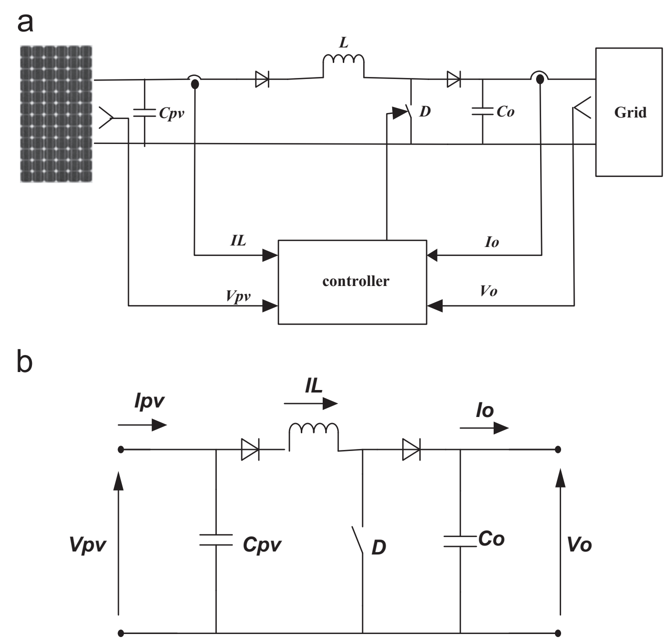

Fig. 16. (a) Hardware implementation of Slide mode control. (b) Equivalent circuit for Slide mode control.

power output and hence change in power ΔP is zero, also when panel is short circuited $V_{PV}=0$, power output and change in power ΔP is again zero and in between these two extreme points there is a voltage $V_{PV}=V_{MPP}$ where again $\Delta P(\, d\,P_{PV}\ /d\,V_{PV})=0$. This voltage $V_{PV}=V_{MPP}$, where change in power is zero can be obtained using bisection search theorem where $V_{PV}=V_{OC}$ and $V_{PV}=0$ are the two extreme points. This voltage is tracked using DC/DC converter and changing its duty cycle. BST requires no derivative of power and voltage to track MPP so system requirement is simple and hardware implementation is simple, also every time duty-cycle is obtained by halving the sum of previous value and current value which makes system fast and number of sensors required is also one.

4.10. Slide mode control method

This method is based on the sliding mode control theory; this method is mostly used for nonlinear systems. It provides control of power converter which tracks the MPP under the condition varying irradiance [41–44]. The system consists of a DC/DC boost converter to transfer power to load from PV panel. The boost converter consists of a power switch D, on–off control of this switch controls the output voltage of the converter, also can be used to track MPP by operating panel at V_{MPP} (voltage at maximum power point) shown in Fig. 16(a) and (b). Mathematical derivation of slide mode control is given in Appendix A.

The MPPT speed is faster with the increase in switching but power output and voltage output fluctuations increases. The efficiency of the MPPT is high as compared to other conventional methods [59].

4.11. Temperature based MPPT

This is another MPPT method which is simple in implementation; cost wise is also cheaper and above all has a good tracking factor [67]. Open circuit voltage of the PV cell varies with the cell temperature whereas the short circuit current varies with the irradiance level as depicted by Eqs. (2) and (3) discussed in Section 2.1 of this article also. The temperature based method uses temperature sensors for tracking MPP, as MPP varies with temperature and MPPT algorithm along with temperature function is used to track MPP [45–47]. But this method suffers from certain disadvantages also, like PV array temperature is not uniform throughout also calibration of temperature sensor is a problem for precision measurement which may cause wrong tracking also [47].

4.12. Gradient descent method

This MPPT algorithm is suitable for fast changing environmental conditions; it also improves the efficiency during tracking as compare to other conventional methods. The method is based on numerical calculation which is used to solve nonlinear problems to optimize some objective functions [48], in MPPT, power is the objective function. Gradient descent method is applied to maximize the power by avoiding the problem of oscillations around MPP. This method is based on the fact that when the operating voltage is in the range of zero and open circuit voltage ($0 \le V \le V_{OC}$), the change in power with respect to voltage (dP^2/dV^2 and dP/dV) and are decreasing functions. When the operating point is close to V_{MPP} the change in power with respect to voltage is small and at MPP, $(dP/dV\,)=0$. So, change in power with respect to voltage is the criterion to select the steps for perturbation. The steps should be large when the operating point is far away from the MPP, while it should be small when the operating point is near the MPP. Thus the oscillations around MPP can be reduced and MPP can be tracked during rapidly changing atmospheric conditions also system becomes much faster and stable.

4.13. Transient based MPPT

This type of technique is used in single stage configuration where PV voltage or current is controlled by inverter to track MPP. This method is different from other conventional methods as it does not contain energy buffer stage DC/DC, also it is based on the MPP detection during transient process, introduced according to the irradiance change but is not based on continuous perturbation [49]. Whenever there is a change in irradiance, current changes and so changes the power, but voltage does not

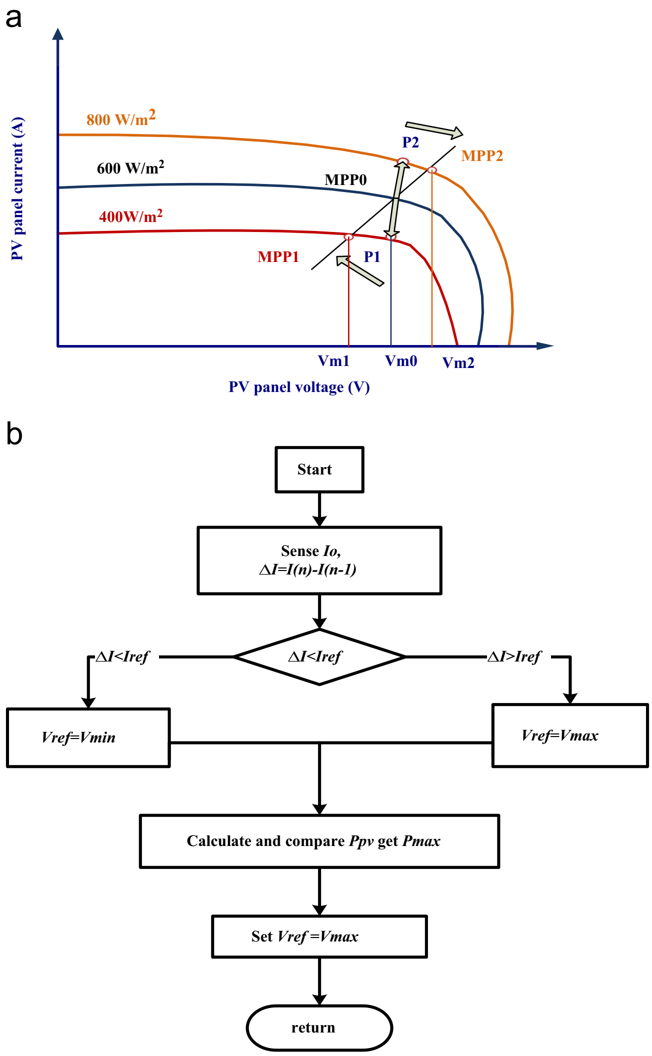

Fig. 17. (a) Transient maximum power point tracking, *V–I* curve. (b) Flowchart.

changes much so only current is required to be sensed in this method. *P–V* curves for three different insolations and flowchart in Fig. 17(a) and (b).

- Initially let the insolation is 600 W/m^2, the operating point is at MPP0, $V_{REF}=V_{MO}$ and $P_{PV}=P_{MO}$.
- Let the insolation increases to 800 W/m^2, voltage output of the panel does not change much due to capacitor C_{PV} (used in parallel to reduce voltage ripple), but current increases and power increases to P_2, new operating point on the new *P–V* curve at 800 W/m^2. Now the reference voltage is changed from $V_{REF}=V_{MO}$ to a large value $V_{REF}=V_{M2}$, the operating point shifts towards right to the MPP corresponding to this insolation that is MPP2 and power output of the panel becomes, $P_{PV}=P_{M2}$, voltage is set to $V_{REF}=V_{M2}$.
- Let the insolation decrease to 400 W/m^2 the power output also decreases to new operating point P_1 which is not MPP so reference voltage is reduced to some value so that operating point shifts toward left to new MPP1. New power is sampled and compared, once the maximum power is sensed the reference value of the voltage is set.

In this way transient is sensed, reference voltage is changed accordingly and new MPP is tracked. This method tracks MPP and

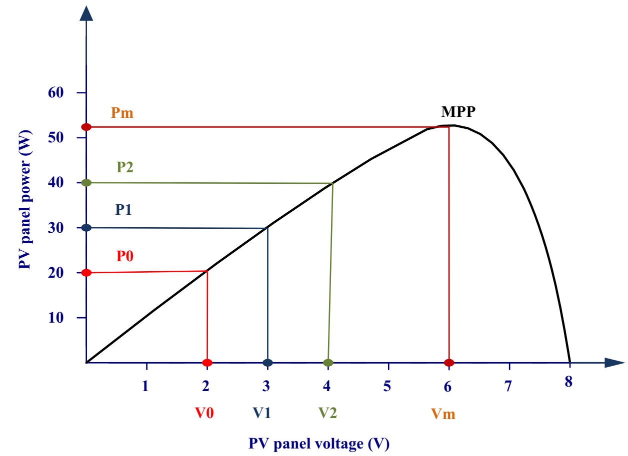

Fig. 18. MPPT based on numerical calculations.

lock it by setting voltage reference hence oscillations in steady state is avoided, MPP during rapidly changing atmospheric conditions can be quickly and accurately computed. System requirement is simple in this method as only current is sensed also no differentiations are required [49]. Another advantage is that the transient process need not be triggered frequently when irradiation changes slowly since power output is sampled and is compared which give rises to double line frequency PV voltage ripple

4.14. MPPT based on numerical calculations

The conventional MPPT algorithms like P&O and INC cannot track MPP in one step as these are iterative approach which senses, calculates and perturbs periodically, so the tracking is slow and not stable at MPP. This problem of low speed, low stability and low accuracy in conventional algorithms can be solved using algorithm based on numerical calculations [50–52]. This algorithm is based on the fact that as PV solar curve is nearly parabolic. Using the parabolic model for solar, with voltage and current as parameters and using quadratic interpolation method, the voltage at MPP is calculated at a particular atmospheric condition [51]. Mathematical explanation of this method is given in Appendix B. This algorithm can calculate the exact voltage value of MPP as it is based on numerical calculations so it can track the MPP in one step unlike conventional (iterative) methods [52].

4.15. Intelligent controlling based MPPT

The MPPT based on this technique can further be classified into three methods:

(1) *Fuzzy logic control (FLC) based MPPT*
(2) *Artificial neural network (ANN) based MPPT*
(3) *Particle swarm optimization (PSO) based MPPT*

These methods have the advantage of working with variable inputs, not needing an accurate mathematical model and handling nonlinearity and are more robust than conventional nonlinear controllers [53–58]. The fuzzy logy controller (FLC) changes the duty cycle of the converter according to the voltage error input and change in error input such that panel output voltage becomes equal to the voltage corresponding to maximum voltage. The voltage error is obtained by comparing the instantaneous array voltage with the reference voltage; the reference voltage corresponds to the maximum array voltage at a particular solar

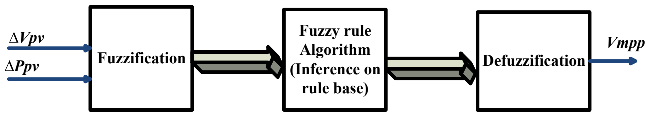

Fig. 19. Fuzzy logic based control technique.

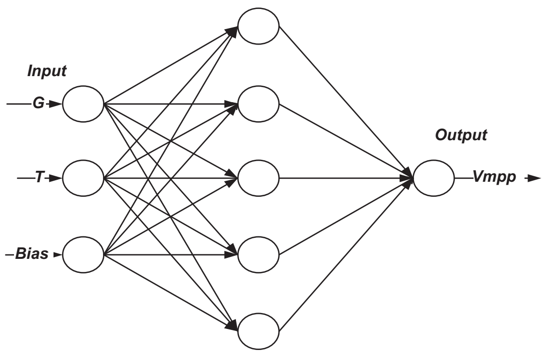

Fig. 20. ANN based MPPT.

insolation at that instant. This maximum voltage and hence the reference voltage changes according to solar insolation. The fuzzy logy controller works in following three stages [53].

- *Fuzzification*: The fuzzification is a process in which the numerical value (Voltage error: V_e and change in error: ΔV_e) are converted into linguistic variable [54]. Then the membership functions for the inputs are chosen in a range of $[-1\ 1]$. In MPPT voltage and power are the two variables which are used in describing the control rules which are to be expressed in terms of fuzzy set with linguistic variables as shown in Fig. 19.
- *Fuzzy knowledge base*: The rule base corresponding to fuzzy inputs and outputs are derived from the system behaviour in the form of IF-THEN rules. Rule base tables are obtained which gives several possible combinations of the degree of supports with varying strengths to the corresponding rules, to satisfy different conditions [54].
- *Defuzzification*: In this process the linguistic variables are converted back to numerical variables as the output of fuzzy controller based on the membership function.

The terminal voltage and reference voltages are sampled periodically and voltage error $V_e = V_{ref} - V_{PV}$, and change in error are computed, then the fuzzy controller determines the control action and computes the desired change in the control voltage for the PWM generator, which further changes the duty ratio of the converter to bring the operating point to MPP.

The ANNs are new emerging technology used to solve complex problems. ANN are used for the on-line estimation of the insolation-dependent reference voltage, since MPP voltages are non linearly related to the solar insolation linear function approximation techniques are not suitable [57,58]. ANN uses feed-forward neural network. Input of ANN consists of solar irradiance and cell temperature. Output voltage at maximum power point is calculated for different inputs as shown in Fig. 20. The information moves from Input, hidden and to output layer only in one direction. The offline ANN can be used to estimate this maximum voltage at a particular insolation. The ANN has an advantage that they do not required detailed information of the system. PSO is another intelligent control technique used nowadays in maximum power point tracking [57,58]. This method is mostly used where multiple maxima are found in *P–V* curve it works efficiently under partial shading condition.

4.16. MPPT using load parameters

In this method the MPP is tracked by monitoring the readings of the load parameters instead of PV panel output parameters. This method is better than other methods in terms of efficiency and simplicity of hardware and software. This method is based on the fact that output current and voltage both increases as the output power increases, so either tracking of current or tracking of voltage means tracking of power. If output current is sensed and accordingly output voltage is controlled then on increasing output voltage if the current also increases means tracker is approaching MPP on the other hand if on increasing voltage if current decrease means tracker is moving away from MPP so current or voltage is maximized rather than power [65]. This method is very advantageous in terms of tracking ability and specially in terms of controller simplicity, since it requires only a single load parameter either current or voltage to be sensed and no multiplications are required to calculate power which further results in less and simple hardware and simple computation. This method is suitable for all practical loads.

4.17. β-MPPT method

This MPPT technique tracks β. β is a variable given by Eq. (19) which depends on reverse saturation current and diode constant [34,61,64,66]. The non-linear *I–V* curve gives this variable β *as.*

$$\beta = l_n\,(I_o \times c) = l_n\,(I_{PV}/V_{PV}) - c \times V_{PV} \tag{19}$$

where: I_o = reverse saturation current and $c = (q/TknN_s)$ and is the diode constant also q is the electronic charge, T temperature in Kelvin, k Boltzmann constant, n is the ideality factor and N_S is the series connected cells. β, is periodically calculated using V_{PV} and I_{PV} and is compared with a constant reference to track MPP. This method is used along with some conventional method to achieve faster MPP tracking. This method is like other variable step method which gives faster tracking speed during varying atmospheric conditions. During initial stage this method is used to track β with larger steps then some conventional method with finer steps is used along the close vicinity of MPP thus giving faster tracking speed and fewer oscillations along MPP.

4.18. Three point MPPT method

As the name indicates, three point method compares power at three points on the *P–V* curve for MPP. The three points are power at current operating point P_n, previous point P_{n-1} and next point P_{n+1}. If the power at P_{n+1} is greater than or equal to power at P_n, positive perturbation is assigned otherwise negative perturbation [69]. If power at P_{n-1} is smaller than that of P_n, positive perturbation is given, otherwise negative perturbation is given as depicted in Table 1. The three power points are compared after each perturbation and duty cycle is changed accordingly. This method is advantageous over other conventional methods as it avoids the oscillation problem around MPP [69,70].

4.19. Parasitic capacitance MPPT method

In this method the effect of PV cell parasitic junction capacitance (C_{PV}), which includes the storage charges in the PV junction cell and stray capacitance, is taken into account to track MPP [70]. Also if the parasitic capacitance is zero the method will be same as incremental conductance. Mathematical derivation of the method is given in Appendix C. The first and second derivative of the PV array voltage is used for maximum power point tracking.

Table 1
Three point method.

S. no	Comparison of three points	Duty-cycle
1	$P_{n+1}>P_n$ and $P_{n-1}<P_n$	Increased
2	$P_{n+1}<P_n$ and $P_{n-1}<P_n$	MPP
3	$P_{n+1}<P_n$ and $P_{n-1}>P_n$	Decreased
4	$P_{n+1}=P_n$ and $P_{n-1}<P_n$	MPP
5	$P_{n+1}=P_n$ and $P_{n-1}=P_n$	MPP
6	$P_{n+1}<P_n$ and $P_{n-1}=P_n$	Decreased
7	$P_{n+1}=P_n$ and $P_{n-1}>P_n$	MPP
8	$P_{n+1}>P_n$ and $P_{n-1}<P_n$	MPP
9	$P_{n+1}>P_n$ and $P_{n-1}=P_n$	MPP

4.20. One cycle control MPPT

A single stage inverter is used in this MPPT method which performs both the functions DC to AC conversion and MPPT [71]. The output current of the inverter which is also the grid current is adjusted according to PV array output voltage. Power is not required to be calculated in this method. This method is cost effective, highly reliable and less complex.

4.21. Variable inductor MPPT

MPPT techniques are based on maximum power transfer theorem, by matching impedance with the help of DC/ DC converter in continuous conduction mode. In this variable Inductor MPPT technique a variable inductor is added in the DC/DC (buck) converter circuit [72]. To achieve stable operation buck converter must operate in continuous current mode. This is made possible with the help of variable inductor. Inductance-current characteristics of the variable inductor depend on the shape of air gap [72]. Characteristic is such that inductance decreases with the increase in current. Addition of variable inductor to the circuit increases range of continuous conduction mode also increases the operating range of the tracker to extract solar power at low solar insolation [72].

4.22. Current sweep MPPT

In this method PV array current sweep waveform is used to obtain *I–V* curve, sweep is repeated periodically to get *I–V* curve and voltage at MPP are also calculated during same periods. This method has advantage of tracking real MPP but complexity is high, speed is slow and both current and voltage are required to be sensed in this method also some power loss takes place as the sweeps takes some time to track MPP [73,74]. Mathematical explanation of the method is given in Appendix D.

4.23. Array reconfiguration method

This method is a mechanical process of tracking electrical parameters. The series combination of PV array increases voltage and parallel combination increases current to the connected load. This is the basis of this MPPT method. PV arrays are connected in series and parallel combinations to obtain MPP at a particular load. This MPPT method is advantageous in case of large load. Mechanical switching adds complexity and reduction in efficiency [75].

4.24. Linearization based MPPT method

This MPPT technique is very simple, fast and cost effective. All the conventional MPPT techniques are based on tracking MPP on non-linear *I–V* characteristics of PV array. Current linearization method is based on linearization of current equation and power equation and determining MPP on the curve at the point of intersection of the solution of these algebraic equations [76]. Mathematical understanding of the method is given in Appendix E Thus, maximum power point can be obtained by intersection of PV array characteristic curve and maximum power line [76].

4.25. State space based MPPT

In this method state space approach, reduces the problem of nonlinear time varying system to ordinary problem of dynamic system stability and then tracks MPP. A state space model using time –averaged switch model is used in this method along with a time varying dynamic feedback controller [77]. This method ensures global asymptotic stability, tracks MPP under varying climatic conditions, and is less affected by parameters and load disturbances [77].

4.26. PV output senseless (POS) MPPT

This MPPT method tracks MPP accurately under varying atmospheric conditions, as compared to complex conventional methods which requires both voltage and current output of the array to be sensed with less accuracy. This method requires only the load current to track MPP [78]. The possibility of tracking failure is very less in this method. This method is based on the fact that the load power is proportional to source power (PV array power). When the duty cycle is increased it causes load current increase and hence this decreases the PV array output voltage. Difference in the old and new duty ratio is calculated and on this basis the change in voltage is determined, and MPP can be tracked.

4.27. A biological swarm chasing (BSC) MPPT algorithm

BSC is an artificial intelligence technique; this is mostly applicable for module integrated PV power system. In this method each module is considered as a particle and MPP is considered as moving target [79]. Particles moves through the problem space, then certain fitness criteria evaluate them and with time the particles accelerates towards better fitness. First, the swarms of particles are initialized assuming swarm size N, and then these particles are perturbed to move. Next the fitness of each particle is checked according to a fitness or objective function at previous $(n-1)$ and present time (n). If the fitness value at previous time sample $(n-1)$ is better than the fitness value at current sample time (n), the best particle is set as the fitness value at $(n-1)$ time and the best location is set as on the current location. The advantage of this method is that it solves the problem of global maxima also efficiency is more than other conventional methods [79].

4.28. System oscillation control MPPT

In this method array voltage is sensed, peak ripple of the PV array voltage is extracted using filters. A constant k_k is determined which is equal to ratio of peak ripple of PV array voltage to PV array voltage [64,69,80]. On the basis of maximum power transfer theorem, converter is operated at a point such that the ratio of the peak dynamic resistance to twice the internal resistance of the array equals to k_k [80]. The method is simple in hardware implementation and it does not require complicated mathematical computations.

4.29. DC-link capacitor droop control MPPT

This MPPT method is mostly used in two stage conversion (DC/ DC and DC/AC Conversion) system. Current on the inverter side is controlled to keep DC link voltage constant, and then the PV array

output power is changed by controlling duty ratio [64] and [81]. The DC link voltage remains constant till the output power is below the maximum power. Above this maximum power limit the DC link voltage decays if the load current is further increased. The load current is again controlled to maintain the DC link voltage constant thereby maintaining system to operate at MPP [81].

5. Analysis and comparison of different MPPT techniques

Different MPPT techniques are compared in this paper on the basis of hardware requirement, speed, accuracy, application, sensors used and cost. Table 2 depicts comparison of different methods on these bases. Incremental conductance method is advantageous as compared to Perturb and observation method

Table 2
Comparison of different MPPT Techniques.

MPPT technique	Classification	PV array dependency	Sensors	Complexity	Tracking accuracy	Economy	Energy tracking factor	Energy conversion stages required	Transient tracking speed	Efficient for partial shading	Applications
VMPPT	Off-line	Yes	V	S	Low	NE	Low	Two	Slow	No	Off-grid
CMPPT	Off-line	Yes	I	S	Low	NE	Low	Two	Slow	No	Off -grid
Look up table	Of-line	Yes	V,I	S	Low	NE	Low	Two	Slow	No	Off-grid
Curve fitting	Off-line	Yes	V	S	Low	NE	Low	Two	Slow	No	Off-grid
P&O	On-line	No	V,I	S	Medium	E	Good	Both	Medium	No	Both
Modified P&O	On-line	No	V,I	C	High	E	Very good	Both	Fast	Yes	Both
INC	On-line	No	V,I	M	High	E	Good	Both	Fast	Yes	Both
Modified INC	On-line	No	V,I	C	Very high	E	Very good	Both	Fast	Yes	Both
INR	On-line	No	V,I	C	High	E	Good	Both	Fast	No	Both
RCC	Indirect	No	V,I	C	High	E	Very good	Both	Fast	Yes	Grid
Power feedback	On-line	No	V,I	S	High	E	Good	Both	Medium	No	Off-grid
BST	Indirect	No	V,I	C	High	E	Good	Two	Medium	No	Off-grid
Slide mode control	On-line	No	V,I	M	Medium	E	Very good	Both	Fast	Yes	Both
Temperature	On-line	Yes	V, Temperature	M	High	E	Low	Both	Medium	No	Off-grid
Gradient descent	Indirect	Yes	V,I	M	High	E	Good	Two	Medium	No	Off-grid
Numerical based	Indirect	Yes	V,I	C	High	E	Good	Two	Medium	No	Off-grid
Intelligent control based	FLC Indirect	No	V,I	C	Very high	E	Very good	Both	Fast	Yes	Both
	ANN Indirect	No	V,I	C	Very high	E	Good	Both	Fast	Yes	Grid
	PSO Indirect	No	V,I	C	Very high	E	Good	Both	Fast	Yes	Off-grid
Load parameters based	Indirect	No	V,I	C	High	NE	Low	Two	Slow	No	Off-grid
β-method	Indirect	Yes	V,I	C	High	E	Good	Two	Fast	Yes	Grid
Three point MPPT	On-line	No	V,I	C	High	E	Good	Both	Fast	No	Both
Parasitic capacitance	On-line	No	V,I	C	Very high	E	Good	Both	Medium	Yes	Off-grid
One cycle control	Indirect	Yes	I	M	High	NE	Good	One	Fast	No	Off-grid
Variable inductor	On-line	No	V,I	M	Medium	E	Good	Two	Medium	No	Off-grid
Current sweep	On-line	No	V,I	C	Medium	NE	Low	Two	Medium	No	Off-grid
Array reconfiguration	Indirect	yes	V,I	C	Low	E	Low	Both	Slow	Yes	Off-grid
Linearization based	Indirect	Yes	V,I	S	Very high	E	Good	Two	Fast	No	Off-grid
State space based	Indirect	Yes	V,I	C	High	E	Good	Two	Medium	Yes	Off-grid
PV Output senseless (POS)	Indirect	Yes	I	S	High	E	Good	Two	Medium	Yes	Off-grid
Biological swarm chasing (BSC)	Indirect	No	V,I	C	Very high	E	Good	Two	Fast	Yes	Off-grid
System oscillation control	Indirect	No	V	C	High	E	Good	Two	Medium	No	Off-grid
DC-link capacitor droop	Indirect	No	V,I	C	High	NE	Very good	Two	Fast	Yes	Both

Note: NE=not very expensive, *E*=expensive, *C*=complex, *S*=simple, M=medium.

in case of rapidly changing atmospheric conditions but the number of sensor required are more and complex derivative calculations increases the hardware requirement and cost. Current and voltage based are, short circuit current and open circuit voltage based techniques, respectively. Both the methods are fast as no derivatives are required to be calculated, and are practical method for MPP estimation [8]. The current based method requires hardware which is more complicated and expensive and has more losses as compared to voltage based method hardware of same rating, accuracy of current based technique is more compared to voltage based technique whereas voltage based technique is more efficient and has fewer losses [9].

The Bisection search technique is simple in hardware requirement as it requires no derivative calculations, economic in implementation as number of sensors required is less and is fast in MPP tracking. The transient based method is different from other conventional methods as it does not contain energy buffer stage (DC/DC). Also it is based on the MPP detection during transient process, introduced according to the irradiance change but is not based on continuous perturbation. The conventional MPPT algorithms like P&O and INC cannot track MPP in one step as these are iterative approach which senses, calculates and perturbs periodically so the tracking is slow and not stable at MPP. The problem of speed, stability and accuracy in conventional MPPT algorithms can be solved using MPPT algorithm based on numerical calculations. Fuzzy logic control (FLC), artificial neural networks (ANN) and particle swarm optimization (PSO) are intelligent methods of MPPT tracking, these methods have the advantage of working with imprecise inputs, not requiring accurate mathematical model and handling nonlinearity. They are more robust than conventional nonlinear controllers. The MPPT based on load parameters method is better than other conventional tracking methods in terms of tracking efficiency and simplicity of hardware and software.

6. Conclusion

Solar energy is the most promising renewable energy source. But it has certain limitations like high initial cost, low efficiency etc. Research is increasingly done to improve system efficiency. This review article aims at providing detailed analysis of PV array characteristics on the basis of temperature and insolation- conditions. Analysis of the PV characteristics reveals the need of MPPT techniques to improve overall system efficiency. A lot of research is being done to improve efficiency of the PV system by extracting maximum power from the PV source. MPPT is a technique employed to extract maximum power available from the PV source. These methods have their own pros and corns on the basis of sensors used, hardware implementation, cost, mathematical calculations etc. A large number of literatures on different MPPT techniques are already available. Choosing MPPT techniques for a particular application, from existing methods is a confusing task as each method has its own merits and demerits.

This review article provides a thorough review of MPPT techniques taken from different literatures, along with their advantages and disadvantages. Working principle of each method is explained in detail along with their mathematical explanations. Paper presents classification of MPPT techniques on the basis of variables and algorithm used, which is useful for selecting an MPPT technique for a particular application. Since the choice of a particular MPPT technique is application specific, these methods are not only reviewed but are analysed and compared at the end of the article. The tabular comparison provided at the end of the article, should be helpful in choosing appropriate MPPT technique on the basis of sensors used, cost, complexity, application, accuracy and speed.

Appendix A. Mathematical derivation of slide mode control method

In Fig. 16(a) and (b), D represents the switch function of the converter, which controls the output power of the PV panel. When $D=1$, the switch is close and when $D=0$, the switch is open [41,64,66]. From Fig. 16(a) and (b)

$$V_{PV}=L\frac{dI_L}{dt}+(1-D)V_O \tag{A1}$$

$$I_L=I_{PV}-C_{PV}\frac{dV_{PV}}{dt} \tag{A2}$$

$$I_o=(1-D)I_L-C_O\frac{dV_O}{dt} \tag{A3}$$

$$\frac{dV_{PV}}{dt}=\frac{(I_{PV}-IL)}{C_{PV}} \tag{A4}$$

$$\frac{dI_L}{dt}=(D-1)\frac{V_O}{L}+\frac{V_{PV}}{L} \tag{A5}$$

$$\frac{dV_O}{dt}=(1-D)\frac{I_L}{C_O}-\frac{Io}{C_O} \tag{A6}$$

$$\frac{dx}{dt}=\begin{bmatrix}\frac{dV_{PV}}{dt}\\ \frac{dI_L}{dt}\\ \frac{dV_O}{dt}\end{bmatrix} \tag{A7}$$

$$f(x)=\begin{bmatrix}\frac{(I_{PV}-IL)}{C_{PV}}\\ \frac{(V_{PV}-V_O)}{L}\\ \frac{(I_L-Io)}{Co}\end{bmatrix} \tag{A8}$$

$$g(X)=\begin{bmatrix}0\\ \frac{V_O}{\mathrm{L}}\\ \frac{-\mathrm{I_L}}{Co}\end{bmatrix} \tag{A9}$$

From the P–V curve MPP is obtained at: $(dP_{PV}/dV_{PV})=0$

$$\frac{dP_{PV}}{dV_{PV}}=\frac{d(I_{PV}V_{PV})}{dV_{PV}}=I_{PV}+\frac{d(I_{PV})}{dV_{PV}}V_{PV}=0 \tag{A10}$$

Switch function is selected as

$$D=\begin{cases}0, & S\geq 0\\ 1, & S<0\end{cases} \tag{A11}$$

$$S(x)=\frac{dP_{PV}}{dV_{PV}}=\left(I_{PV}+\frac{dI_{PV}}{dV_{PV}}V_{PV}\right) \tag{A12}$$

Using Lyapunov function [64]:

$$V=\frac{1}{2}S^2>0 \tag{A13}$$

$$\dot{V}=S\frac{dS}{dt}=\frac{dP_{PV}}{dDeq}\times\frac{d}{dt}\left(\frac{dP_{PV}}{dDeq}\right) \tag{A14}$$

Two results are obtained:

(1) When $S>0$, the system operates on the left of the MPP, $D=0$, V_{PV} is increasing

$$\frac{dV_{PV}}{dt}>0 \tag{A15}$$

$$S\frac{dS}{dt}<0 \tag{A16}$$

(2) When $S<0$ the system is operating in right, $D=1$, V_{PV} is decreasing

$$\frac{dV_{PV}}{dt}<0 \tag{A17}$$

$$S\frac{dS}{dt}<0 \tag{A18}$$

Thus, the system could reach global stability and the switch function tends to zero, whether the system is operating in the left or right of MPP.

Appendix B. Mathematical Explanation of Numerical Calculations Based MPPT

In Fig. 18 V_0, V_1 and V_2 represents the three voltage values at three operating points on the P–V curve, P_0, P_1 and P_2 represents the power values corresponding to the voltage values as in Fig. 18.

$$\mathrm{M}\,(V)=M_0(V)P_0+M_1(V)P_1+M_2+(V)P_2 \tag{B1}$$

where $M\,(V)$ is the quadratic interpolation polynomial [51], $M_0(V)$, $M_1(V)$, $M_2(V)$, are quadratic interpolation basis functions and are given by following equations:

$$M_0(V)=(V-V_1)(V-V_2)/(V_0-V_1)(V_0-V_2) \tag{B2}$$

$$M_1(V)=(V-V_0)(V-V_2)/(V_1-V_0)(V_1-V_2) \tag{B3}$$

$$M_2(V)=(V-V_0)(V-V_1)/(V_2-V_0)(\,V_2-V_1) \tag{B4}$$

and the quadratic interpolation function is expressed [51], as the following equations:

$$\begin{aligned}\mathrm{M}(V)=&(V-V_1)(V-V_2)/(\,V_0-V_1)(\,V_0-V_2)P_0\\&+(V-V_0)(V-V_2)/(\,V_1-V_0)(\,V_1-V_2)\,P_1\\&+(V-V_0)(V-V_1)/(\,V_2-V_0)(\,V_2-V_1)P_2\end{aligned} \tag{B5}$$

To track MPP the derivative of the quadratic interpolation function with respect to voltage ($dM(V)/dV=0$) is equated to zero.

$$\begin{aligned}dM(V)/\mathrm{d}V=&2(k_1+k_2+k_3)V\\&-[k_1(V_1+V_2)+\,k_2(V_0+V_2)\,+k_3(V_0+V_1)]\end{aligned} \tag{B6}$$

where k_1, k_2 and k_3 are denoted as

$k_1=P_0/(V_0-V_1)(V_0-V_2)$,
$k_2=P_1/(V_1-V_0)(V_1-V_2)$,
$k_3=P_2/(V_2-V_0)(V_2-V_1)$.

Voltage at maximum power point is obtained as

$$\begin{aligned}V_{MPP}=&k_1(V_1+V_2)+k_2(V_0+V_2)\\&+k_3(V_0+V_1)/2(k_1+k_2+k_3)\end{aligned} \tag{B7}$$

if voltages V_1, V_2 and V_3 and constant k_1, k_2 and k_3 are known MPP can be tracked.

Appendix C. Mathematical derivation of parasitic capacitance MPPT

The current in the capacitance is given by $IC_{pv}(t)=C_{pv}dV_{PV}/dt$ [64], current sensed is given by

$$\mathrm{Isensed}=I_{PV}-IC_{PV} \tag{C1}$$

$$\mathrm{Isensed}=I_L-I_0\left[\exp^{(V_{PV}+R_SI_{PV}/V_T)}-1\right]-\frac{V_{PV}+R_SI_{PV}}{R_P}-C_{pv}\,d\,V_{PV}/dt \tag{C2}$$

$$\mathrm{Isensed}=F(V_{PV})-Cpv\,d\,V_{PV}/dt \tag{C3}$$

Since first component is a function of voltage and second, current in parasitic capacitance

$$F\,(V_{PV})=Isensed+C_{pv}\,d\,V_{PV}/dt \tag{C4}$$

$$\frac{dF\,(V_{PV})}{dV_{PV}}+\frac{F(V_{PV})}{V_{PV}}=\frac{dIsensed}{dV_{PV}}+\frac{Isensed}{V_{PV}}+Cpv\left(\frac{V_{\dot{P}V}}{V_{PV}}+\frac{V_{\ddot{P}V}}{V_{\dot{P}V}}\right)=0 \tag{C5}$$

where

$$\frac{dF\,(V_{PV})}{V_{PV}},\ Cpv\left(\frac{V_{\dot{P}V}}{V_{PV}}+\frac{V_{\ddot{P}V}}{V_{\dot{P}V}}\right)$$

and

$$\frac{F\,(V_{PV})}{V_{PV}}$$

are the instantaneous conductance, the incremental conductance and the induced ripple from the parasitic capacitance, respectively [64].

Appendix D. Mathematical derivation of current sweep MPPT

The function for sweep waveform is directly proportional to its derivative

$$f(t)=ks\frac{df(t)}{dt} \tag{D1}$$

where ks is proportionality constant [63,64,66], The PV array power output is given by

$$P_{PV}(t)=V_{PV}(t)I_{PV}(t)=V_{PV}(t)f(t) \tag{D2}$$

$$\frac{dP_{PV}(t)}{dt}=V_{PV}(t)\frac{df(t)}{dt}+f(t)\frac{dV_{PV}}{dt}=0 \tag{D3}$$

From (D1) and (D3)

$$\frac{dP_{PV}(t)}{dt}=\left[V_{PV}(t)+ks\frac{dV_{PV}}{dt}\right]\frac{df(t)}{dt}=0 \tag{D4}$$

Solution of Eq. (D1) is

$$f(t)=C_1e^{(t/ks)} \tag{D5}$$

Constant C_1 in this Eq. (D5) is chosen equal to maximum PV array current I_{max} and ks to be negative will lead to

$$f(t)=I_{max}e^{(-t/\tau)} \tag{D6}$$

where $\tau=-ks$, from Eqs. (D1) and (D4)

$$\frac{dP_{PV}(t)}{d(t)}=\left[V_{PV}(t)+ks\frac{dV_{PV}}{dt}\right]\frac{dI_{PV}(t)}{dt}=0 \tag{D7}$$

where, I_{PV} can be calculated using Eq. (D5) and V_{MPP} using Eq. (D7). This method is complex and convergence speed is slow.

Appendix E. Mathematical derivation of linearization based MPPT method

$$I_{PV}=I_L-I_O\,\{[e^{(q/AKT)(V_{PV}+R_S*I_{PV})}]-1\} \tag{E1}$$

Thus, for the MPPT, the first curve is represented by $f(P_{PV}, I_{PV})=0$ on the $P_{PV}-I_{PV}$ plane [64–66]: $f(P_{PV}, I_{PV})=P_{PV}-V_{PV}*I_{PV}=0$

$$P_{PV}-\frac{q}{AKT}I_{PV}\ln\left[\frac{I_L+I_O-I_{PV}}{I_O}\right]-I_{PV}{}^2\,R_S\,=0 \tag{E2}$$

At the maximum power point

$$\frac{dP_{PV}}{dI_{PV}}=0 \tag{E3}$$

From Eqs. (E1)–(E3)

$$g(P_{PV}, I_{PV}) = P_{PV} - \alpha I_{PV} \ln \frac{\alpha_{IPV}{}^2}{(P_{PV} - I_{PV}{}^2 R_S) I_o} + I_{PV}{}^2 R_S = 0 \quad \text{(E4)}$$

where

$$\alpha \cong \frac{AKT}{q}$$

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